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LCA FOR AGRICULTURE

Comparing nutritional value and yield as functional units in the environmental assessment of horticultural production with organic or mineral fertilization

The case of Mediterranean cauliflower production

Julia Martínez-Blanco · Assumpció Antón · Joan Rieradevall · Massimo Castellari · Pere Muñoz

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Abstract
Background, aim, and scope We report the environmental assessment of the cultivation cycle of cauliflower (*Brassica oleracea* L. var. *botrytis*), chosen due to its high levels of natural bioactive compounds, using different fertilization practices. The functional units used during the impact assessment were linked with the quantity produced, considering different units of commercialization, or with the cauliflower quality, considering its antioxidant compounds content. Although nutrient content has been described and used as a possible functional unit, using antioxidant compounds as a functional unit has not previously been published.
Method Three cultivation options with similar dosages of total nitrogen were considered: using mineral fertilizers (M) alone or mineral fertilizers plus compost, with a high (C_H) or a low (C_L) dosage. During the cultivation period, the soil characteristics and nitrogen and moisture content of the fruit were monitored, and the yield and the fruit size were analyzed. In addition, the glucosinolates and the phenolic compounds (sinapic acid, phenols, and flavonoids) content were assessed for the three options. Life cycle assessment (LCA) was used to determine the environmental impacts of the whole cauliflower production cycle, including production of mineral and organic fertilizers, fertilizers transport, and crop stage.
Results and discussion Commercial yields were higher for cultivation options with M and C_L than for option C_H, while higher levels of bioactive compounds were detected in the latter. For C_H and C_L, eutrophication, global warming and ozone layer depletion potentials were generally lower and photochemical oxidation potential was always higher than for the M option, regardless of the functional unit. Regarding functional units involving production (yield, fruit and dry matter harvest), there were higher impacts with the C_H cultivation option than with M for abiotic depletion, acidification, photochemical oxidation, and cumulative energy demand. When the differences in bioactive compounds content (total sinapic acid derivatives and total phenols) were sufficiently high, this was reversed, with C_H having lower impacts for all the environmental categories apart from photochemical oxidation and abiotic depletion.
Conclusions and perspectives The differences in the magnitude of individual environmental impacts between culti-

J. Martínez-Blanco (✉) · J. Rieradevall
Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain
e-mail: julia.martinez@uab.cat

A. Antón · P. Muñoz
Institute of Research and Technlology in Agrifood Sector (IRTA), Environmental Horticulture, 08348 Cabrils, Barcelona, Spain

A. Antón
Departament d'Enginyeria Quimica, Universitat Rovira i Virgili (URV), 43007 Tarragona, Spain

J. Rieradevall
Chemical Engineering Department, Universitat Autònoma de Barcelona (UAB), 08193 Bellaterra, Barcelona, Spain

M. Castellari
Institute of Research and Technology in AgriFood Sector (IRTA), Food Technology, Finca Camps i Armet, 17121 Monells, Girona, Spain

vation options, and also the order, were highly dependant on the functional unit considered. When functional units associated with production and total phenols content were considered, the C_H cultivation option had the highest impact in four out of seven categories, whereas for the functional unit involving sinapic acid content, this cultivation option had the least impact in five out of seven categories.

Keywords Compost · Food products · Functional unit · Life cycle assessment · Mineral fertilizers · Nutritional compounds

1 Introduction

The area under organic farming in the EU-27 increased by 7.4% between 2007 and 2008 (Rohner-Thielen 2010). Due to the increasing consumer demand for environmentally friendly food products (Antón 2004; Podsedek 2007; Montero et al. 2009; Romero-Gámez et al. 2009; Lairon 2010), real alternatives to current intensive production methods need to be supported by scientific research (Schau and Fet 2008; Blengini and Busto 2009).

More attention is also being paid to the role of diet in human health and in food safety and security (Podsedek 2007; Lairon 2010), which means that secondary metabolites content is a factor that must also be considered during the assessment of agriculture systems. Antioxidants and the antioxidant capacity of food, nutraceuticals, botanicals, and other dietary supplements have recently attracted the attention of the industry, scientists and consumers, because of potential health benefits (Sun and Tanumihardjo 2007).

Antioxidant compounds in food, which include phenolic compounds and glucosinolates, are linked with cell maturation and therefore promote cardiovascular health, inhibit the growth of cancerous tumors and cell masses, slow the aging process in the brain and nervous systems, and lessen the risk and severity of neurodegenerative diseases (Pyo et al. 2004; Benbrook 2005; Podsedek 2007; Gratacós-Cubarsí et al. 2010). Although glucosinolates have rather low antioxidant activity, products of their hydrolysis can also protect against cancer (Podsedek 2007).

A wide range of factors can influence the mix of secondary metabolites that a plant manufactures, as they have direct roles in plant responses to stress (Benbrook et al. 2008; Lairon 2010). Gratacós-Cubarsí et al. (2010) indicated that these factors include genetic and agronomical factors (i.e. species, variety, crop management strategies and circumstances, postharvest storage, plant stage, cooking, etc.). In addition, the positive effects on health depend on the dosage ingested (Nilsson et al. 2006).

Despite the potential importance for human well-being, only a limited number of studies on the effects of these factors have been specifically carried out, as described by Benbrook et al. (2008) and Lairon (2010). Focusing on crop management strategies, which include soil type and chemistry, available nitrogen and levels of other nutrients, moisture levels, temperature, and pest pressure (Benbrook 2005; Benbrook et al. 2008), some case studies have compared organic and conventional agriculture. These studies indicate a tendency towards nutritional superiority but lower yields of organic products (Benbrook 2005; Benbrook et al. 2008; Lairon 2010). Wang and Lin (2003) presented the first study assessing the effect of compost application on flavonoid levels and total antioxidant capacity of strawberries. De Pascale et al. (2006) have demonstrated that both the farming system and N rate affect carotenoid content and antioxidant activity of tomato fruits. In fields where high levels of nitrogen are readily available, plants can, and normally do, grow rapidly and to a relatively large size, but concentrations of polyphenols and some vitamins are typically lower. Benbrook (2005) has referred to this phenomenon as the “dilution effect”.

Although compost application appears to be a good fertilizing complement (e.g., improving soil characteristics), as demonstrated in previous environmental studies, it has not performed as well as systems with mineral fertilizers (per ton or kilo of agricultural product) in most impact categories (Sharma and Campbell 2003; Hansen et al. 2006; Blengini 2008; Blengini and Busto 2009; Martínez-Blanco et al. 2009; Martínez-Blanco et al. 2010a).

Members of the Brassicaceae family are widely consumed and considered to have an important role in human nutrition (Gratacós-Cubarsí et al. 2010) partly due to their high content of secondary metabolites. According to Podsedek (2007), the secondary metabolites in Brassica vegetables are basically vitamins, carotenoids, glucosinolates and phenolic compounds which have an important antioxidant activity. Glycosides of kaempferol and quercetin, and their derivatives in combination with hydrocinnamic acids as well as sinapic acid derivatives, have been found to be the major phenolic compounds in the Brassicaceae family (Gratacós-Cubarsí et al. 2010). These vegetables also have a large group of glucosinolates, which are sulfur-containing compounds (Nilsson et al. 2006) on which there has been considerable research.

Life cycle assessment (LCA) is a suitable methodology for the environmental evaluation of food systems (Audsley 1997; Williams et al. 2006; Blengini and Busto 2009). Nevertheless, as pointed out in previous studies on the environmental performance of compost use in agriculture (Sharma and Campbell 2003; Martínez-Blanco et al. 2009), the importance of introducing some positive aspects of

compost, such as the improvement of soil characteristics and the increase in nutrient content, should not be underestimated.

The functional unit is the basis for comparisons between different systems in LCA (ISO 2006). Adequately selecting a functional unit is of prime importance because different functional units can lead to different results for the same product system. Even though the primary function of food is nutrition, in most articles on the environmental assessment of food production, the functional unit is based on mass or volume. The use of 1 ton or kilo for normalization of the inventory and the environmental impacts is particularly common in agricultural production. In some studies, the functional units have been defined as other mass or volume parameters (e.g., dry mass), the economic value (e.g., the market price), the quality of the product (e.g., the nutrient, energy or protein content of the product or its keeping quality), the consumer's reaction to the product or land use (e.g., hectare), among others (Hayashi et al. 2006; Mourad et al. 2007; Reap et al. 2008; Schau and Fet 2008).

Here, we varied the dosage of compost applied to quantify the potential effects on the content of the main nutritional compounds in cauliflower, and then carried out an environmental assessment of the whole system from a productivity and nutritional standpoint. As far as we know, although nutrient content has been described and used as a possible functional unit (Schau and Fet 2008), this is the first time glucosinolates or phenolic compounds have been used.

The first goal of this research was to assess and compare the yield and size of cauliflower using three cultivation options that combine mineral fertilizers and compost. The second was to establish the potential effects of the fertilization on the content of antioxidant compounds. The third goal was to assess the environmental performance of the three options considering five functional units. The first two functional units were linked with commercial yield and commercial fruit, representing the units of commercialization, per mass or per fruit unit, two common units of measure for cauliflower which depend on the market. The third unit used was a kilo of dry matter, which expresses the real content in proteins, minerals, vitamins, etc. but not the water content, a variable that depends highly depends on several parameters (such as irrigation and time of day, among others). The two last functional units were related with total sinapic acid derivatives content and total phenols content, two important nutritional quality parameters connected with the antioxidant activity, one of the most highly appreciated components of cauliflower. Bioactive compounds with non-significant differences between cultivation options were not considered as a potential functional unit.

2 Methodology

This section has been split into four parts as follows: the experimental methodology for the agricultural production; the laboratory measurement of the bioactive compounds; the statistical methods; and, finally, the LCA goal and scope.

2.1 Agricultural methodology

Cauliflower was chosen from the four crops cultivated using a horticultural Mediterranean rotation (chard, tomato, cauliflower, and onion) due to its high levels of natural bioactive compounds (Podsedek 2007; Gratacós-Cubarsí et al. 2010), so increasing the likelihood of finding significant differences in content of these compounds.

2.1.1 Climate conditions, soil, and cultivation period

The experimental plot was at the SELMAR research fields in Santa Susanna (Barcelona, NE Spain), with a Typic Xerothent soil and Mediterranean climate. The plants (*Brassica oleracea* L. var. *botrytis*, commercialized as Trevi®) were transplanted on 28 September 2007 at a plant density of 2.1/m^2. The cauliflower was cultivated for 110 days and harvested from 11–18 January 2008. For the period 1990–2008, the average annual evapotranspiration was 771 mm, and rainfall, 649 mm. Climate data were obtained from a weather station next to the field. Cultivation followed the best available techniques for integrated crop management (Bradley et al. 2002; MAPA 2002), aiming to compare efficient systems for resources, energy, and emissions.

2.1.2 Water and fertilizers application

Crops were micro-sprinkler irrigated three times a week depending on the tensiometer reading that determined the matric water potential evapotranspiration demands of the soil. The total irrigation and rainfall water are shown in Table 1.

Three cultivation options were used: only mineral fertilizers (M); mineral fertilizers plus low-dose compost (C_L) with a third of the total nitrogen needs for cultivation supplied by compost and the rest by mineral fertilizers; and mineral fertilizers plus high-dose compost (C_H) with two thirds of the total nitrogen needs supplied by compost. Compost alone without mineral nitrogen added was not an option, due to the particular characteristics of the irrigation water, with a high concentration of nitrates (Martínez-Blanco et al. 2009; Martínez-Blanco et al. 2010b).

The experiment had a block design with three replicates for each cultivation option (a total of 9 blocks of 39 m^2).

Table 1 Mineral fertilizers and compost, nitrogen and irrigation water applied for each cultivation option

Substance	Cultivation option		
	C_H	C_L	M
Fertilizer dose (g/m^2)			
Compost[a]	1,996.06	998.03	0.00
HNO_3[b]	32.80	32.50	33.80
KNO_3	0.00	34.30	71.40
Nitrogen dose (gN/m^2)			
Organic nitrogen[c]	8.11	4.15	0.00
Mineral nitrogen[d]	9.93	14.56	20.10
Total nitrogen	18.04	18.71	20.10
Water dose (l/m^2)			
Irrigation water	231	229	238
Rainfall water	80	80	80

C_H mineral fertilizers plus high-dose compost, C_L mineral fertilizers plus low-dose compost, *M* mineral fertilizers alone

[a]The proportion of the total compost allocated to the cauliflower crops taking into account the nitrogen uptake (17-month rotation period). The moisture content of the compost applied to the experimental plots was 27% and the organic matter content was 53% for dry material. In relation to heavy metals, class A compost (Martínez-Blanco et al. 2010a, b).

[b]Nitric acid, 60%. The high nitrogen content in water was accounted as addition of synthetic nitric acid.

[c]Nitrogen from compost. Nitrogen available the first year after spreading of compost it is the easily hydrolysable organic nitrogen (Pare et al. 1998; Saña 1999; Moral and Muro 2008).

[d]Nitrogen from mineral fertilizers, irrigation water and rainfall.

The doses of fertilizers were calculated by taking into account the soil nutrient content and the agricultural necessities with the aim of comparing cultivation options with similar available nutrient rates. The mineral fertilizers used for the C_L and M cultivation options were potassium nitrate and nitric acid. The high nitrogen content of the irrigation water (192 g/m^3 of NO_3^-), a result of the excessive use of mineral fertilizers in the region (Muñoz et al. 2008b), was also considered a mineral source of nitrogen for the three options. Table 1 shows the fertilizers and N supplied to the crop in the three cultivation options.

Compost is not normally applied to every crop, but in cycles of 1–2 years, to distribute environmental burdens associated with the transport and machinery used. Consequently, only the corresponding proportion of the total compost for each crop was taken into account, with the allocation calculated according to total nitrogen uptake by the crop from the experimental data of the horticultural rotation. For this study, compost was applied once in a rotation of 17 months.

2.1.3 Soil and yield measurements

Several soil samples were taken during the cultivation period of cauliflower to measure the evolution of moisture and nitrogen content (NO_3-N) at three different depths (Doltra and Muñoz 2010).

Total and marketable yield in the whole plot area were determined per block and per cultivation option during harvest time, and the diameter of a representative sample of 30 commercial cauliflowers per cultivation option (ten per replicate) was measured. Five cauliflowers per cultivation option were sampled and immediately (within 2 h) frozen at −80°C, for bioactive compounds measurement described in the next section.

At four points during cultivation, aerial samples of the cauliflower (distinguishing between leaves, fruit and stems) were taken from each block. The wet weight was measured for each sample, and the moisture was determined with a drying temperature of 65°C until constant weight. Two plants from each block (with a fruit, leaf, and stem sample), at each of the four sampling points, were dried and the N content analyzed by the Kjeldahl method (Doltra and Muñoz 2010). Micro and macro-nutrient content was also measured for these samples using ICP-OES spectrometry.

2.2 Bioactive compounds analysis

Sinapic acid derivatives, flavonoids and glucosinolates, the most important nutritional compounds of cauliflower (Nilsson et al. 2006; Gratacós-Cubarsí et al. 2010), and total phenols were assessed.

2.2.1 Chemicals

Methanol and acetonitrile, HPLC gradient grade, were obtained from Baker (J.T. Baker, Deventer, The Netherlands). The commercial standards for the Folin–Ciocalteau 2 N reagent, Na_2CO_3 and formic acid, were purchased from Sigma-Aldrich-Fluka (Madrid, Spain). Glucosinolate and phenolic compound standards were obtained from Sigma-Aldrich-Fluka (Madrid, Spain), Phytolab GmbH & Co. KG (Vestenbergsgreuth, Germany) and ChromaDex Inc. (Santa Ana, CA, USA).

Standard stock solutions of the commercial standards, at 1 g/l, were prepared by dissolving in MeOH:Water (60:40, *v*/*v*).

2.2.2 Sample treatment

Cauliflower samples were vacuum packed in PE/aluminum bags, frozen at −80°C and analyzed within 2 months. Frozen cauliflower florets were minced in a Robot-coupe

Blixer 3. Samples were extracted and analyzed as described by Gratacós-Cubarsí et al. (2010).

2.2.3 UPLC-MS/MS analysis

An aliquot of 1.5 g of frozen sample was mixed with 75 μl of internal standards (GTP and Q3R) and 7.5 ml of methanol, and maintained at 70°C for 15 min.

Extracts were refrigerated in an ice water bath and centrifuged at 10,000 rpm for 10 min at 4°C in a Beckman J2-MC centrifuge (Beckman Instruments INC., Palo Alto, CA, USA).

Glucosinolates, flavonoids, and sinapic acid derivatives were quantified with an Acquity UPLC-MS/MS system (Waters, Millford, US) equipped with a diode array detector (DAD) and a triple quadrupole mass spectrometer (TQD) operated in negative electron-spray ionization mode (ESI−). An aliquot of 2 ml of the clean extract was evaporated to dryness with nitrogen and reconstituted with 1 ml of mobile phase A (5% ACN in 0.1% formic acid), filtered through a PTFE 0.2 μm filter, and 5 μl injected.

Chromatographic separation was using a BEH Shield C18 (1.7 μm particles, 1.0 mm id×150 mm) column (Waters Corp., Manchester, UK) set at 35°C at a flow rate of 0.130 ml/min. The linear gradient of the mobile phase was from 100% A (0.1% formic acid: 95:5 *v*/*v* ACN) and 0% B (0.1% formic acid: 40:60 *v*/*v* ACN) to 50% A and 50% B at 23 min.

Glucosinolates and flavonoids were quantified by MRM, considering one MS/MS transition for each compound. Sinapic acid was quantified on the basis of the DAD signal (λ=330 nm). Sinapic acid derivatives were quantified as sinapic acid equivalents (SAE), taking into account their molecular weight. Matrix-matched regression curves were calculated for each compound by plotting analyte/internal standard peak area ratio against the spiking concentration/internal standard concentration.

2.2.4 Total phenols

Total phenols were evaluated following the method of Singleton and Rossi (1965), with minor adjustments. An aliquot of 1.5 g of frozen sample was added to 7.5 ml of methanol and extracted as previously described. One milliliter of clean extract was added to 3 ml of water and 0.25 ml of Folin–Ciocalteau 2 N reagent. After 1 min the sample was mixed with 2.5 ml 20% Na_2CO_3 and 3.25 ml of water, and then thoroughly mixed. After 2 h, the color development was spectrophotometrically measured at 725 nm with a Shimadzu UV-240 Graphicord (Shimadzu Europe GmbH, Duisburg, Germany). Total phenols content was expressed as caffeic acid equivalents (CAE) with a caffeic acid calibration curve.

2.3 Statistics

Yield and fruit size data and bioactive compound data were analyzed with the Enterprise Guide software package (SAS Institute Inc. 2006). Analysis of variance was conducted using the General Linear Models procedure, and the least significant difference test (LSD, p<0.05) was used to establish differences between treatments.

2.4 Life cycle assessment methodology

LCA was used for evaluating the potential environmental impacts of cauliflower cultivation considering its entire life cycle. According to the ISO 14040 (ISO 2006), an LCA is divided into four steps: the goal and scope definition (stated below), the inventory assessment (Section 2), the impact assessment (Section 3.3), and, finally, the interpretation of the results (Sections 3.3 and 4). A more detailed description of the system can be found in Martínez-Blanco et al. (2009; 2010b).

2.4.1 Description of the system

As mentioned above, the three cultivation options, characterized by the type of fertilization, were C_H, C_L, and M.

The five stages used in the study were: compost production, mineral fertilizers production, compost transport, mineral fertilizers transport (both from the factory to the fields) and the cultivation stage including six sub-stages (Table 2). The cultivation options with compost, C_H and C_L, considered the five stages while the M option did not consider the production and transport of compost.

The whole system, from obtaining raw materials required for the manufacture of the different elements to the management of generated waste, was considered for each stage.

2.4.2 Functional units

For different bases of comparison between the cultivation options, five functional units were considered including mass (a ton of commercial cauliflower), which is the most usual functional unit for food production LCA (Antón et al. 2005; Hayashi et al. 2006; Williams et al. 2006; Mourad et al. 2007; Reap et al. 2008; Schau and Fet 2008; Blengini and Busto 2009; Martínez-Blanco et al. 2009; Iribarren et al. 2010). The four additional bases dealt with the potential units of commercialization (including mass and fruit), the dry matter and the nutritional content of commercial cauliflower (considering the content of total sinapic acid derivatives and total phenols). The five functional units included in the study, which were the reference against which input and output flows were normalized, are summarized in Table 3.

Table 2 Quality and origin of data for cauliflower cultivation in a Mediterranean open field. Experimental (E), local (L) and regional (R) data

Stage		Processes / sub-stages included	Comments	Source E	Source L	Source R
Mineral fertilizers production		Production at plant including the production infrastructure, transport of raw materials, synthesis of the chemical components required and the deposition or treatment of waste generated [a,b]; dosages.	Mineral fertilizers considered (HNO_3 and KNO_3).	x	x	x
Mineral fertilizers transport		Mineral fertilizers transport from the plant to the crops [a,b]; distances.	Produced in Germany (1,950 km in a lorry of >16t MAL).		x	x
Compost production		Collection and transport of municipal organic waste [c,d]; water, electricity and diesel consumed in the industrial composting process [c,d]; building and main machinery [c,d]; solid waste fraction landfilled [a,c,d]; biofilter characteristics and gaseous emissions [d,e]; and the physicochemical characteristics of compost.	Source separated collection of OFMSW and VF; decomposition in tunnels, with forced aeration and irrigation systems; biofiltration for the exhaust gases	x	x	x
Compost transport		Compost transport from the plant to the crops [a,c]; distances.	Produced in the composting plant (66 km in a lorry of >3.5–16t MAL).		x	x
Cultivation stage	Fertirrigation infrastructure	System design; components production and transport [b,c]; and transport and management of waste [b,c].	Including tanks, plumps, electrovalves, pipes, rods and micro-sprinklers.	x	x	
	Phytosanitary substances	Type of substances needed; substance doses [g]; and phytosanitary substances production [a].	Two applications. Minimal doses.	x		x
	Machinery and tools	Machinery and tools needed (type, hours of operation, characteristics and fuel consumption) [c]; machinery and tool production and maintenance [a]; diesel production and emissions; and transport and management of waste [a,c].	Including tractor, agricultural machinery and harvesting elements.	x		x
	Irrigation	Water consumption; electricity consumption of pumps; and rainfall.	Water supplied were showed in Table 1	x	x	
	Fertirrigation emissions	Emissions of NH_3, N_2O, NO_x and N_2 to air and emissions of NO_3 to water [h,i].	Emissions produced by nitrogenous mineral or organic fertilizers	x		x
	Carbon sequestration	Carbon still bound to soil after 100 years	Section 2.2.		x	x

[a]Swiss Centre for Life Cycle Inventories 2009
[b]Martínez-Blanco et al. 2010b
[c]Martínez-Blanco et al. 2009
[d]Martínez-Blanco et al. 2010a
[e]Colón et al. 2009
[f]MAPA 2002
[g]MMAMRM
[h]Bentrup and Küesters 2000
[i]Audsley 1997

2.4.3 Quality and origin of the data in the inventory

The broad system of study required a detailed data-collection process. As shown in Table 2, most of this data were obtained experimentally by the authors in the plots and in the composting facility (e.g., industrial composting inputs and outputs, gaseous emissions from aerobic degradation, fertirrigation infrastructure design, irrigation, and rainfall). Furthermore, the parameters of soil characteristics, fertilizer dosages, harvests and fruit size were also obtained from the experimental plots. When local information was not available, bibliographical sources and the

Table 3 Functional units considered in the environmental assessment

Functional unit	Acronym	Related parameter	Data[a]
1 t of commercial cauliflower	CY	Commercial yield	Table 4
1 commercial fruit	CF	Commercial fruit	Table 4
1 kg of commercial dry matter	DM	Commercial dry matter harvest	Table 4
1 kg of SAE	SA	Total sinapic acid derivatives content	Table 5
1 kg of CAE	PH	Total phenols content	Table 5

[a]Data used for the normalization of the inventory and the environmental results

SAE sinapic and equivalents, *CAE* caffeic acid equivalents

ecoinvent database v2.1 (Swiss Centre for Life Cycle Inventories 2009) were used to complete the life cycle inventory. Type of data and references used are specified in Table 2.

The tunnel composting plant, described in detail in Martínez-Blanco et al. (2009; 2010b), was at Castelldefels, in the Barcelona metropolitan area (41°17′18″N, 1°58′16″E, Spain). The experimental plots were located in Santa Susana (41°38′27″N, 2°43′00″E, Spain) and are described above.

2.4.4 Impact distribution procedure

For the management of several waste flows generated within the boundaries of the system, the "cut-off" method (Ekvall and Tillman 1997) was used. According to this method, each system was assigned the burdens for which it was directly responsible.

Regarding conflicts with distribution of environmental burdens, they are very common in agrifood (Blengini and Busto 2009) and waste treatment systems as these systems usually have one or more further functions in addition to waste management, such as by-products or energy production, and are usually at the limit of the system boundaries defined for the LCA. When comparing the impacts of the three cultivation options, it must be remembered that compost production, as well as providing a fertilizer, is an option for organic fraction of municipal solid waste (OFMSW) and vegetal fraction (VF) treatment, which is not the case in the production of mineral fertilizers. To take this it into account and trying to avoid allocation, as advised in the ISO 14040 (ISO 2006), the boundaries of the system should be expanded (Finnveden 1999) to make the two fertilizer systems comparable and the environmental burdens of another way of treatment of the organic waste should be subtracted. Although dumping of organic waste is theoretically very restricted in Europe (The Council of the European Union 1999), it is still common practice in the municipal waste management. Furthermore, the alternatives are also multi-functional ways of treatment, such as incineration and anaerobic digestion that have a major capacity for energy recovery. Therefore, the environmental burdens of dumping organic waste were subtracted from those options that include composting, so that only its fertilizing function was compared.

2.4.5 Categories of impact and LCA methodology

Six impact categories (abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion and photochemical oxidation potentials) defined by the CML 2001 (Guinée 2001), and cumulative energy demand as an energy flow indicator, were considered. Owing to the lack of relevant data for the assessment of most of the phytosanitary substances, toxicity categories were not assessed. The SimaPro v. 7.2.2 program (PRé Consultants 2010) was used for impact analysis, with the obligatory classification and characterization phases defined by the ISO 14040 standard regulation (ISO 2006).

3 Life cycle inventory

The description of stages and sub-stages, and the processes included in each one, are shown in Table 2. Most of the considerations were according to the inventory descriptions of Martinez-Blanco et al. (2009, 2010b) but considering all the agricultural data for cauliflower cultivation obtained from the experimental plots. In addition, the inclusion of the high nitrogen content of water, the calculation of carbon sequestration in the soil and the subtraction of the composting-avoided burdens are stated below.

3.1 Nitrogen content in the irrigation water

The nitrogen content of the irrigation water was considerably higher (192 g/m^3 of NO_3^-) than the limit established by the European Directive 91/676 (European Parlament and European Council 2006) for ground water (50 g/m^3 of NO_3^-) as a result of the excessive use of mineral fertilizers in the region (Muñoz et al. 2008b). The major additional contribution of nitrogen from the irrigation water was taken into account as synthetic added mineral fertilizer for two reasons. Firstly, to reflect its influence on the results, particularly for the cultivation options with combined compost and mineral fertilizer options. We verified that

compost without addition of other fertilizers was not enough from an agricultural point of view, at least during the first few years of compost application (Muñoz et al. 2008a; Martínez-Blanco et al. 2010b). Secondly, to present more general results and to allow the comparison and extrapolation of data to other areas (with or without contamination of groundwater by nitrates). In other circumstances, irrigating with nitrate-polluted water may be considered making good use of a waste flow. For the inventory, irrigation water was given a virtual concentration of 50 g/m^3 of NO_3^- and the extra 142 g/m^3 of NO_3^- were accounted as added mineral fertilizer (HNO_3), considering its production, transport and application. The irrigation water used during the cultivation period is shown in Table 1.

3.2 Carbon sequestration

After the compost is produced and applied to the land, it continues to degrade, releasing more carbon dioxide and forming humic compounds that then mineralize much more slowly than the organic matter originally applied in the compost. Compost applications may therefore increase the store of soil organic matter (Smith et al. 2001). The Intergovernmental Panel on Climate Change clearly identified this long-term carbon sequestration as one of the possible GHG mitigation measures for agriculture at an early stage. Apart from promoting the build-up of carbon in the soil, Favoino and Hogg (2008) stated that the application of high-quality composted products would contribute to restoring soil fertility and health, preventing desertification and erosion, and avoiding floods.

Previous studies have estimated that the carbon still bound to soil after 100 years is between 2% and 14% of the carbon introduced with compost (Smith et al. 2001; Hansen et al. 2006; Favoino and Hogg 2008; Boldrin et al. 2009). An average value of 8% was used in this study, similar to the value reported by Smith et al. (2001) and Hansen et al. (2006). For cauliflower cultivation, the total carbon introduced was 197 g per kg of compost, therefore carbon sinks of 31.5 and 15.7 g/m^2 were considered for C_H and C_L, respectively. This sink was accounted for in the calculation of greenhouse gas emissions as a negative contribution to the total emissions.

3.3 Avoided burdens of dumping OFMSW and VF in landfill

As previously mentioned, in the allocation procedure for the multi-functional systems, dumping was the method selected as an alternative to composting for organic waste management. Environmental burdens for dumping the same amount of OFMSW and VF as used in the production of the compost used in C_H and C_L were subtracted from the total impacts of these cultivation options.

The process of dumping OFMSW or VF was calculated with the Calculation Tool for waste disposal in Municipal Sanitary Waste Landfill MSWLF from the ecoinvent database v2.1 (Swiss Centre for Life Cycle Inventories 2009). These organic wastes were assimilated in the waste flow “compostable material”, in the calculation tool and the impurities material content was also included. To this was added the collection and transport of waste to the local landfill in a municipal waste collection lorry of 21 t MAL (a distance of 17 km), including the production and cleaning of the collection containers. The construction of the landfill and road access, the machinery operation, the combustion of methane without energy recovery, and the land used, were all considered with a time limit of impact of 100 years (Doka 2007).

4 Results and discussion

We present the results for the yield, fruit sizes, and the bioactive compound contents, followed by the environmental results for the functional units considered, using these data.

4.1 Agricultural results: yield and size parameters

The yield and the fruit size parameters are shown in Table 4. Significant statistical differences were observed for commercial yield between the option with high dosage of compost and the two others. The commercial yield obtained for C_L and M were 27% and 39% higher than that for C_H, respectively, while no significant differences were found between the C_L and M cultivation options. These values were within the average levels expected for this method of cauliflower cultivation in the area (Doltra and Muñoz 2010). Differences between non-commercial yields were lower than for commercial ones, and non-significant, while there was a significant difference between C_H and M for total yield.

The fruit average weights were significantly different between the three cultivation options (see Table 4), being 41% and 11% greater for M than for C_H and C_L, respectively. There was a significant difference between the average dry weight of fruit in cultivation options M and C_H, being 28% higher in the M cultivation option. There was no significant difference in this parameter between M and C_L. The fruit average diameter was 6% greater in C_L compared to C_H but non-significant differences were found between these options and M.

Table 4 Parameters of yield and fruit size

Parameter	Unit	Cultivation option			LSD[a]
		C_H	C_L	M	
Cauliflower yield					
Commercial yield	t/ha	12.2[b]	15.5[a]	17.0[a]	–
Non-commercial yield	t/ha	36.8	43.6	45.8	ns
Total yield	t/ha	49.0[b]	59.1[ab]	62.7[a]	–
Fruit size parameters[b]					
Fruit average wet weight	g	705.3[c]	894.0[b]	994.4[a]	–
Fruit average dry weight	g	74.2[b]	89.1[a]	94.8[a]	–
Fruit average diameter	cm	19.2[b]	20.3[a]	20.2[ab]	–

C_H mineral fertilizers plus high-dose compost, C_L mineral fertilizers plus low-dose compost, *M* mineral fertilizers alone

[a]Least significance different taste. Different letters (a, b, c) indicate significant effect and "ns" non-significant effect at p=0.05 (Section 1.3).

[b]These parameters were assessed for commercial fruits, considering commercial fruits those without dark patches, and tight and compact, with a diameter of more than 18 cm.

4.2 Nutritional results: bioactive compounds content

The concentrations of total sinapic acid derivatives and total phenols (Table 5) were significantly higher in C_H samples than in the other two cultivation options, C_L and M, for which the values were very similar. This was also true for individual compounds considered within total sinapic acid derivatives. For total sinapic acid derivatives and for the individual compounds, except for 1-sinapoyl-2-feruloyldi-glucoside, the concentration for C_H was between 75–89% higher than for M. The total phenols content in cauliflower samples was 24% higher in C_H than in M.

As shown in Table 5, significant differences were found in some of the individual, but not in total, glucosinolates and flavonoids. While the concentrations of total glucosinolates were equal in C_H and M, significant differences were detected for some of the individual compounds without a specific trend. The concentrations were lowest in C_L for all the individual compounds and therefore for the total glucosinolates. Although they are not significant differences, the content of total glucosinolates for the cultivation options C_H and M were double that of the C_L content. The total content of flavonoids in the C_L and C_H samples was 22% and 10% higher than for M samples, respectively, with a significant difference between C_H and M for one of the individual compounds of the total flavonoids (see Table 5).

Diverging trends were found in the bioactive compounds content for C_H and C_L, particularly for total glucosinolates and the individual compounds, despite the differences not being significant. It is not easy to explain the behavior of the bioactive compounds we observed in the different cultivation options. Glucosinolates and phenolic compounds are secondary metabolites and could be affected indirectly by different agronomic factors, such as the fertilization practices or the available nitrogen levels, as described earlier. Their distribution in specific areas of the fruit, as well as differences in the water content of the tissues, could also influence the final result. More research is needed in this area to identify potential connections between all these factors.

4.3 Environmental results

4.3.1 Total environmental impacts

As mentioned previously, five different functional units were considered to compare the environmental impacts between the cultivation options: the yield, the fruit, the dry matter and the content of two nutritional compounds (see Table 3). The results are presented in Table 6 and Fig. 1.

The environmental impacts of cultivation option C_H, for each functional unit, are shown in Table 6. From these results, and using the percentages from Fig. 1, the absolute values could be calculated for the other two cultivation options.

In Fig. 1, for each impact category, the results are shown as a percentage of the environmental impact of M, which was considered as 100% for the five functional units. For example, the abiotic depletion potential (ADP) for C_H and C_L, considering the functional unit of commercial yield, had almost 22% and 62% more impact than M option, respectively.

For the eutrophication potential (EP) and the global warming potential (GWP) categories (see Fig. 1), C_H had the minimum environmental impacts and M the maximum

Table 5 Concentration of bioactive compounds in cauliflower samples

Bioactive compound	Unit	Cultivation option			LSD[a]
		C_H	C_L	M	
Total sinapic acid derivatives	mg SAE/kg	40.9[a]	23.3[b]	23.3[b]	–
Sinapic acid	mg/kg	1.2	0.6	0.7	ns
1,2-disinapoyl-diglucoside	mg SAE/kg	10.1[a]	5.9[b]	5.8[b]	–
1-sinapoyl-2-feruloyldiglucoside	mg SAE/kg	3.5	3.2	2.7	ns
1,2,2′-trisinapoyldiglucoside	mg SAE/kg	20.2[a]	10.1[b]	10.7[b]	–
1,2′-disinapoyl-2-feruloyldiglucoside	mg SAE/kg	6.0[a]	3.5[b]	3.4[b]	–
Total phenols	mg CAE/kg	275.5[a]	213.3[b]	222.0[b]	–
Total Glucosinolates	mg/kg	169.6	84.3	164.3	ns
Glucoiberin	mg/kg	128.1	65.4	137.0	ns
Sinigrin	mg/kg	1.5	1.0	1.6	ns
Glucoraphanin	mg/kg	26.0	10.1	12.5	ns
Progoitrin	mg/kg	0.8	0.4	0.4	ns
Glucoalyssin	mg GTPE/kg	0.6[b]	0.6[b]	1.1[a]	–
Glucoiberverin	mg GTPE/kg	1.1	0.3	1.4	ns
Glucoerucin	mg/kg	1.5[a]	0.3[b]	0.6[b]	–
4-OH-Glucobrassicin	mg GTPE/kg	1.1	0.3	0.7	ns
Glucobrassicin	mg GTPE/kg	3.8	2.4	3.9	ns
Metoxiglucobrassicin	mg GTPE/kg	2.8	2.3	3.8	ns
Neoglucobrassicin	mg GTPE/kg	1.3	0.7	0.7	ns
Total Flavonoids	µg Q3RE/kg	790	876	718	ns
Kaempferol-3-diglucoside-7-diglucoside	µg Q3RE/kg	309[a]	134[ab]	127[b]	–
Quercetin-3-diglucoside-7-glucoside	µg Q3RE/kg	453	714	568	ns
Kaempferol-3-diglucoside-7-glucoside	µg Q3RE/kg	28	28	24	ns

SAE sinapic acid equivalents, *CAE* caffeic acid equivalents, *GTPE* glucotropaeolin equivalents; *Q3RE* Rutin equivalents

C_H mineral fertilizers plus high-dose compost, C_L mineral fertilizers plus low-dose compost, *M* mineral fertilizers alone

[a]Different letters indicate significant effect. "ns" non-significant effect at $p=0.05$ (Section 1.3)

for all functional units. The environmental impacts of C_H and C_L for both impact categories were negative due to the avoided burdens by composting and not dumping municipal organic waste (see Section 3.3.). Although leaching during cultivation was considered in the inventory, fertilization dosages were adjusted to the real needs of the crops and therefore few nutrients were leached. The environmental impacts of cultivation option C_H were between 32 and 68 times less than for M for EP and between 4 and 9 times lower for GWP, depending on the functional unit.

For photochemical oxidation potential (POP), the impact order was reversed (C_H>C_L>M) in all the categories. The high impacts of options with compost were due to the emissions of volatile organic compounds during organic waste decomposition in the composting facility (Martínez-Blanco et al. 2010b). The impacts for cultivation option C_H

Table 6 Total environmental impacts for the cultivation option C_H (mineral fertilizers plus high-dose compost) considering the five functional units

Impact category	Unit (per FU)[a]	Functional unit[a]				
		CY per t	CF per fruit	DM per kg DM	SA per kg SAE	PH per kg CAE
Abiotic depletion potential	kg Sb eq	3.01E+00	2.12E−03	2.86E−02	6.14E+01	1.09E+01
Acidification potential	kg SO_2 eq	5.14E+00	3.63E−03	4.89E−02	1.05E+02	1.87E+01
Eutrophication potential	kg PO_4^{3-} eq	−1.79E+01	−1.26E−02	−1.70E−01	−3.65E+02	−6.50E+01
Global warming potential	kg CO_2 eq	−3.45E+03	−2.43E+00	−3.28E+01	−7.03E+04	−1.25E+04
Ozone layer depletion potential	kg CFC-11 eq	2.55E−05	1.80E−08	2.43E−07	5.21E−04	9.26E−05
Photochemical oxidation potential	kg C_2H_4 eq	3.02E+00	2.13E−03	2.87E−02	6.16E+01	1.10E+01
Cumulative Energy Demand	MJ eq	6.69E+03	4.72E+00	6.36E+01	1.37E+05	2.43E+04

[a]See Table 3 for the acronyms of functional units

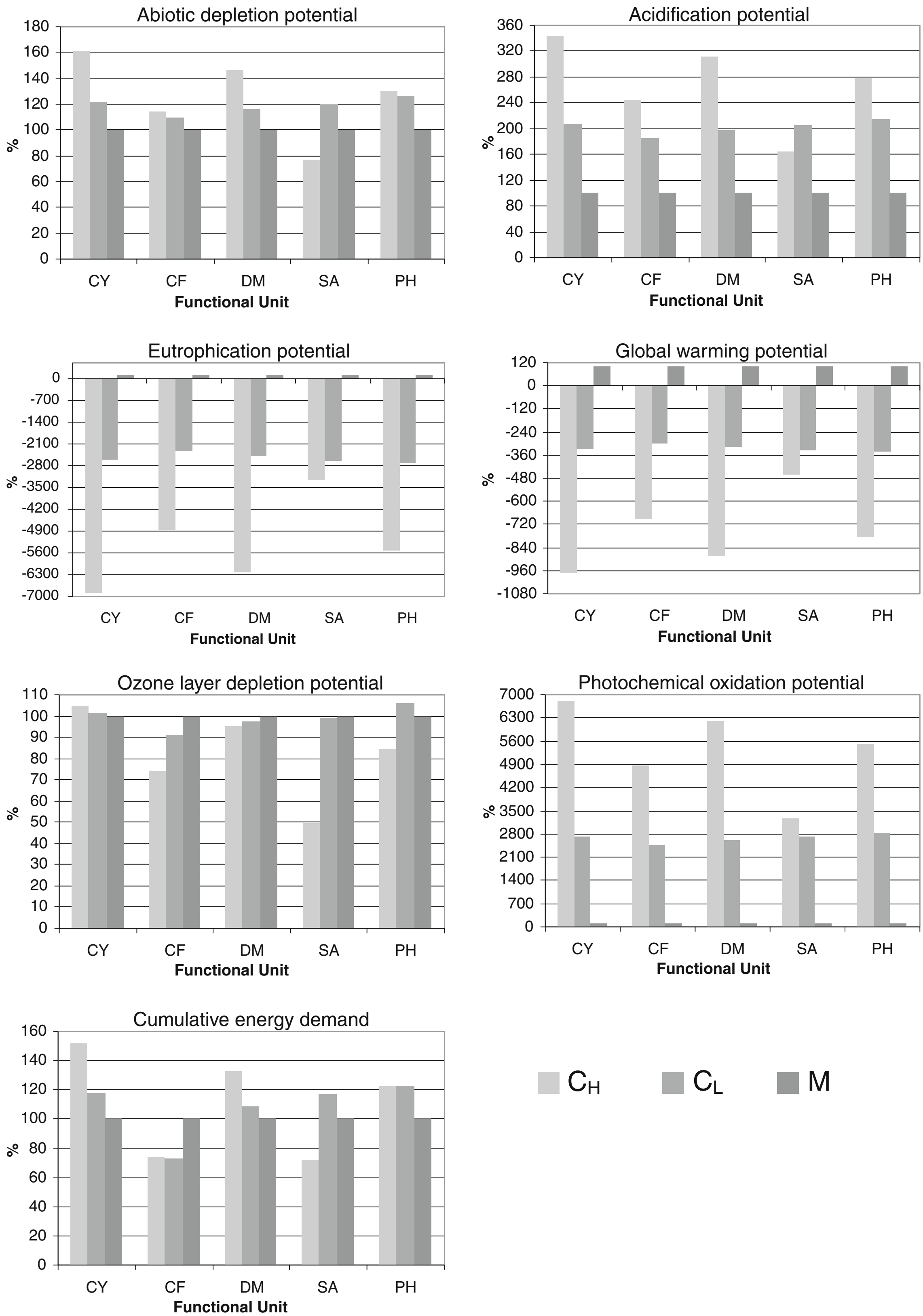


Fig. 1 Total environmental impacts (percentage) for the three cultivation options considering the five functional units. *See Table 3 for the acronyms of functional units. C_H mineral fertilizers plus high-dose compost, C_L mineral fertilizers plus low-dose compost, M mineral fertilizers alone

were between 32 and 67 times greater than for M, depending on the functional unit.

For these impact categories (EP, GWP, and POP), the impact order did not vary with the functional unit, but the magnitude of the differences between cultivation options changed considerably (see Fig. 1). For example, the impact distances between C_H and C_L, considering the total sinapic acid derivatives content as a functional unit, were lowest for EP, GWP, and POP as the lower production of C_H was compensated for by its higher sinapic acid content.

Regarding ADP and acidification potential (AP), the order of impact was $C_H > C_L > M$ for all the functional units apart from sinapic acid derivatives content, for which C_L had the higher impact. The cultivation option C_H had between 14% and 61% more impact than M, depending on the functional unit, for ADP and between 62% and 244%, for AP.

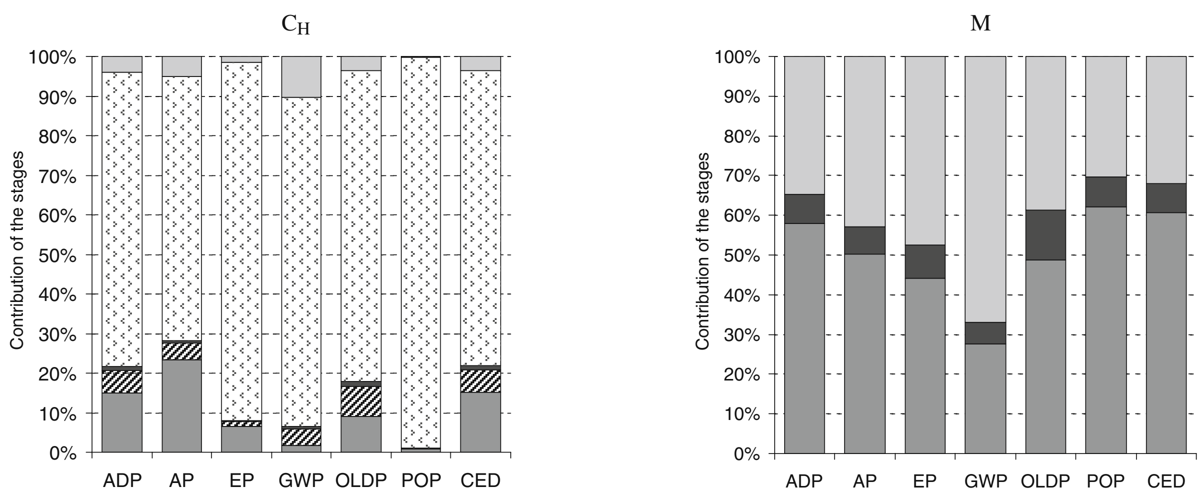
For the impact categories ozone layer depletion potential (OLDP) and cumulative energy demand (CED), the impact order between the cultivation options changed considerably depending on the functional unit. For the former, the impact order for three out of the five functional units was $M \geq C_L > C_H$, due to the impacts saved by not dumping municipal organic waste. The cultivation option C_H had between 5% and 50% less impact than M, depending on the functional unit. Considering commercial yield, dry matter harvest and total phenols content as functional units, the C_H cultivation option had the maximum impact and M the minimum for CED, with differences up to 52% between them.

Other functional units were not used in the study as data were not available or non-significant differences between cultivation options were measured. Total glucosinolates content, total flavonoids content and other principal micro and macro-nutrients were assessed but were not considered as functional units as no significant differences were detected between the three cultivation options. Another potential functional unit related with the price of the product (i.e., one euro or one dollar paid for a quantity of commercial cauliflower) would be of interest if market prices differed depending on the type of fertilization or the nutritional content. Other functional units used in previous studies, for example the energy or protein content of fruit or the reaction of the consumer to the food product, were not considered due to the lack of data.

4.3.2 Contributions to environmental impacts

An environmental contribution analysis was carried out for the three cultivation options, considering the five stages (described in Section 2.4.1) and the avoided burdens of dumping OFMSW and VF in landfill (Section 3.3). These results are independent of the functional unit considered. The results of the analysis are shown in Fig. 2 for the cultivation options C_H and M, the two extreme cases.

The compost production stage clearly had the greatest contributor to the total environmental impact of C_H, between 74% (ADP) and 99% (POP). As has been pointed out in previous publications (Martínez-Blanco et al. 2010a; Martínez-Blanco et al. 2010b), the energy consumption of the facility, the organic waste collection, the VOC emissions and the solid waste fraction to landfill are mainly



C_H

	ADP	AP	EP	GWP	OLDP	POP	CED
Mineral fertilizers production	4.0%	5.0%	1.4%	10.3%	3.5%	0.2%	3.6%
Compost production	74.4%	66.9%	90.7%	83.1%	78.6%	98.7%	74.6%
Mineral fertilizers transport	0.9%	0.6%	0.2%	0.6%	1.2%	0.0%	0.9%
Compost transport	5.8%	4.1%	1.3%	4.3%	7.6%	0.3%	5.8%
Cultivation stage	14.9%	23.4%	6.4%	1.6%	9.2%	0.8%	15.2%
Avoided burdens landfill	-65.1%	-45.8%	-370.3%	-306.9%	-82.8%	-30.0%	-68.2%

Impact categories

M

	ADP	AP	EP	GWP	OLDP	POP	CED
Mineral fertilizers production	34.7%	42.9%	47.4%	67.0%	38.7%	30.4%	31.9%
Compost production	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Mineral fertilizers transport	7.4%	6.9%	8.5%	5.3%	12.5%	7.6%	7.4%
Compost transport	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Cultivation stage	57.9%	50.3%	44.1%	27.7%	48.8%	62.1%	60.7%
Avoided burdens landfill	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Impact categories

Fig. 2 Contribution to total environmental impacts by stages (plus avoided burdens of dumping OFMSW and VF in landfill)

responsible for the high environmental impacts of this stage. The total impacts in Fig. 1 were the summation of the contributions of the five stages, with the avoided burdens subtracted. These subtracted burdens were particularly important for EP, GWP, and OLDP, which are the impact categories most affected by the dumping of organic waste: the CO_2 and CH_4 emissions contribute to category GWP and the emissions and lixiviates of nitrogen and phosphorous contribute to EP and OLDP (Martínez-Blanco et al. 2009).

For the M cultivation option, impacts were mainly distributed between the cultivation stage, contributing between 28% and 62% depending on the impact category, and the mineral fertilizers production, that contributed with 30–67% to the total impacts.

5 Conclusions and perspectives

Cauliflower cultivation in Mediterranean fields was chosen due to the high levels of natural bioactive compounds. Apart from functional units linked with the production, others connected with potential differences in the content of these compounds, depending on the type of fertilization, were used.

Higher commercial yield and higher wet average weight of fruit were found for the M cultivation option, with only mineral fertilizers, than for options with compost (C_H and C_L). Where there were significant differences in content of bioactive compounds, the content in C_H was higher than in M, (for total sinapic acid derivatives and total phenols).

For EP and GWP, cultivation options with compost had negative impacts for all functional units, and for POP, the impact order was C_H>C_L>M regardless of the functional unit. The environmental results obtained for the other four impact categories (ADP, AP, OLDP, and CED) depended on the functional unit considered.

With production functional units (commercial yield, commercial fruit and commercial dry matter harvest), when commercial yield was considered, M had lower environmental impacts than C_H, apart from the EP and GWP categories, due to the higher yield of cauliflower. The number of cauliflowers cultivated per unit area was similar between cultivation options but the fruits for options with compost were smaller and had higher environmental impacts per commercial fruit, apart from EP, GWP, and OLDP. As the differences between cultivation options for moisture content were not significant, the impact distribution for commercial dry matter harvest was similar to that for commercial yield functional unit.

Comparing the environmental impacts of the three cultivation options depending on their bioactive compounds content, the results were reversed for sinapic acid derivatives content, apart from POP, due to the higher content of this compound in the C_H cultivation option. Although C_H presented the highest contents when there was a significant difference in these compounds, the highest levels were found in C_H, but C_L did not follow the same trend. The content of total sinapic acid derivatives in C_H is twice that of C_L and M, so that, in all categories apart from POP and AP, C_H had the lowest impacts. In contrast, smaller differences were measured for total phenols content, so that the order of the cultivation options with this functional unit was similar to that of commercial production but with lower differences.

Measuring the differences in bioactive compounds for cauliflower grown with only mineral fertilizers or adding compost is costly and difficult, with a huge number of potential bioactive compounds. As a result, it is difficult for a farmer using compost to demonstrate the higher value of their agricultural product and increase the market price. National statistics and further research in this field is necessary to establish clear trends that would affect the price of agricultural products and promote healthier consumption. More research is necessary on the effects of different cultivation techniques, with fertilizing alternatives, apart from the increase or decrease in yield. In particular, the quantification of the total production of secondary metabolites and their real benefits to human health could contribute to better knowledge of nutrition, aid institutional decision making and lead to more accurate labeling of products. Strategies are also needed to maintain or increase yield using organic fertilizers without reducing their beneficial effect on nutrition.

From the results and trends reported in this study, the importance of comparing environmental impacts with several functional units is clear, especially for food products assessment. Functional units related with economic, quality, safety, and consumer satisfaction parameters, among others, can give considerably different results for environmental impacts.

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